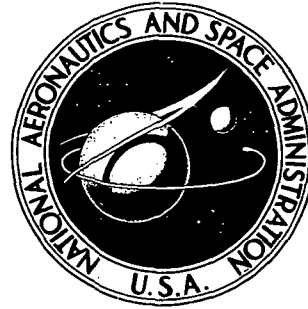


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**GAS-INJECTION-START AND
SHUTDOWN CHARACTERISTICS
OF A 2- TO 15-KILOWATT
BRAYTON POWER SYSTEM**

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GAS-INJECTION-START AND SHUTDOWN CHARACTERISTICS OF A 2- TO 15-KILOWATT BRAYTON POWER SYSTEM

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SUMMARY

Two methods of starting the Brayton power system have been considered: using the alternator as a motor to spin the Brayton rotating unit (BRU), and spinning the BRU by forced gas injection. The first method requires the use of an auxiliary electrical power source. An alternating voltage is applied to the terminals of the alternator to drive it as an induction motor. This starting method has been reported in the literature; only gas-injection starts are discussed in this report. The gas-injection starting method requires high-pressure gas storage and valves to route the gas flow to provide correct BRU rotation.

An analog computer simulation was used to size hardware and to determine safe start and shutdown procedures. The simulation was also used to define the range of conditions for successful startups. Experimental data were also obtained under various test conditions. These data verify the validity of the start and shutdown procedures.

INTRODUCTION

The Lewis Research Center is currently investigating a 2- to 15-kilowatt Brayton power system for electric power generation. The Brayton power system is a self-contained power generating system suitable for space or remote ground applications.

The Brayton system under study consists of five subsystems. These subsystems are used for heat-source input, power conversion, gas management, electrical distribution, and heat rejection. The system is designed to be used with various heat sources. It uses a gas mixture of helium and xenon to transfer energy from the heat source to the rotating components. The energy from the rotating components is then converted to electrical energy by means of an alternator.

During the early phases of system design it was necessary to determine start and shutdown procedures and to define the hardware required to implement these procedures. To aid in this determination, an analog computer was used to simulate the dynamics of the Brayton power system. The simulation was then used to investigate various start and shutdown procedures and to generate specifications for the required hardware (ref. 1).

Two methods of starting the Brayton power system have been considered: using the alternator as a motor to spin the Brayton rotating unit (BRU), and spinning the BRU by forced gas injection. The first method requires the use of an auxiliary electrical power source. An alternating voltage is applied to the terminals of the alternator to drive it as an induction motor. This starting method is reported in references 2 and 3.

The gas-injection starting method requires high-pressure gas storage and valves to route the gas flow to provide correct BRU rotation. This report presents data on gas-injection starts only. The purpose of this report is to present the start and shutdown characteristics of the Brayton power system as determined by using both early analytical predictions and test results from the Space Power Facility at the Plum Brook Station of Lewis Research Center.

SYSTEM DESCRIPTION

A schematic diagram of the Brayton power system is shown in figure 1. The major subsystems are used for heat source input; power conversion; gas management; electrical distribution, which includes the voltage and speed controls and the engine controls; and heat rejection.

Although the power conversion subsystem is designed to be used with several different types of heat sources, an electric heat source was used for initial ground testing. The power conversion subsystem is a closed gas loop which includes the Brayton rotating unit (turbine, alternator, and compressor), the recuperator, and the waste heat exchangers. The working fluid is a mixture of helium and xenon at the molecular weight of krypton (83.8). The turbine and compressor are single-stage radial-flow machines. The alternator is a brushless Lundell generator. These three rotating components are mounted on a common shaft which is supported by gas bearings. The BRU is designed to operate at a speed of 36 000 rpm.

The gas management subsystem incorporates the necessary valves and gas-storage devices required for starting and shutdown.

The electrical subsystem consists of the voltage- and speed-regulating controls and the engine controls. Speed is maintained with a solid-state parasitic-load control. The engine controls include the automatic controls necessary to operate the system in a programmed manner for starting and shutdown. The Brayton power system is designed to

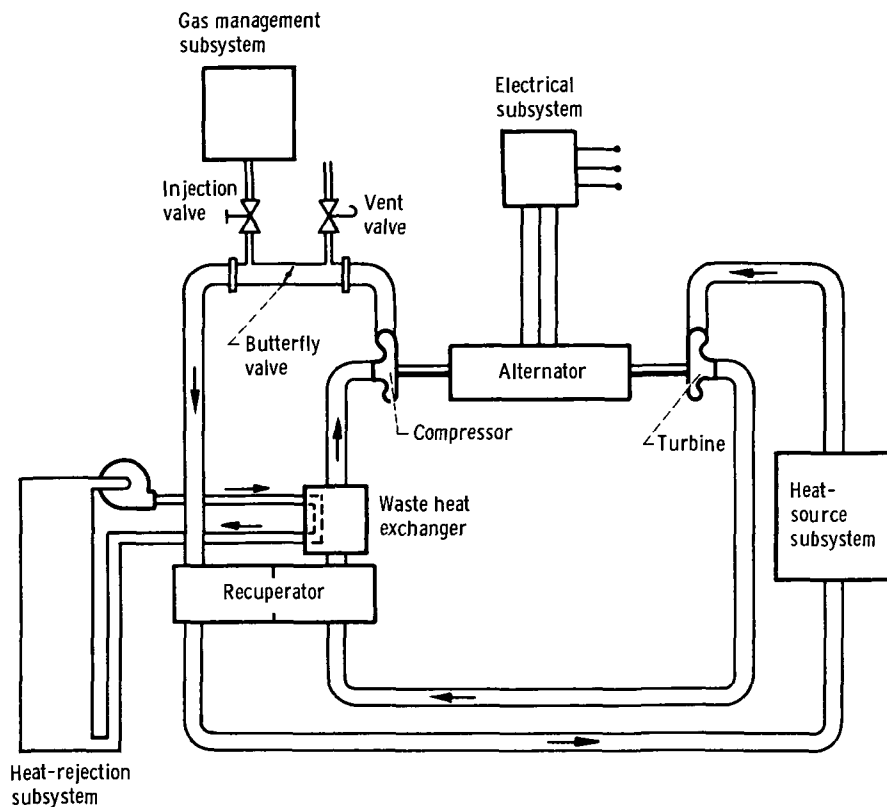


Figure 1. - Schematic diagram of a 2- to 15-kilowatt Brayton cycle power system.

deliver from 2 to 15 kilowatts (three-phase, 208/120 V, 1200 Hz), depending on the heat-source input power and the system pressure level. A more detailed description of the system can be found in references 4 and 5.

This system was simulated on the analog computer early in the design phase of the program in order to assist in making hardware decisions. The analog computer simulation was a dynamic representation of the Brayton system which combined individual component models into a complete system model. This model provided the ability to optimize the response of the system by conveniently studying a wide variety of component characteristics. A description of the analog simulation can be found in the appendix.

STARTING CONSIDERATIONS

Description of Start

A gas-injection start begins with the BRU at zero speed, no gas in the system, and no power from the heat source. The heat-source heat exchanger is preheated to a tem-

perature near design (1140 K, 2060⁰ R). Gas is injected into the system through the heat-source heat exchanger and the turbine, causing the BRU to rotate. The gas then passes through the compressor and is vented to space. This is the open-loop portion of startup. After the system is closed and design speed is reached, the gas inventory is adjusted to produce the desired operating power level. Following this there is a period of approximately 20 minutes during which the radiator and the gas-loop heat exchangers are reaching temperature equilibrium.

Valves Required

Valve system design. - The gas-loop hardware required to implement an injection start consists of three valves: an injection valve to allow gas to enter the system, a butterfly valve to prevent reverse gas flow during injection, and a vent valve to allow for venting gas to space during the open-loop portion of the start. The vent valve is also used to vent gas after shutdown to allow for restart. In the Brayton engine configuration, these valves are located near the compressor discharge, as shown in figure 1. This location was chosen because of its low temperature and to avoid compressor surge in the event of a valve failure. The primary function of these valves is to permit acceleration of the BRU to rated speed in the open-loop configuration (i. e. , with the injection and vent valves open and the butterfly valve closed). During starting and shutdown, the gas management subsystem must also supply the gas bearings with gas prior to their becoming self-acting.

Valve sizing. - The analog studies indicated that for a given injection flow and turbine inlet temperature there was a minimum vent valve size for which the BRU would reach rated speed with open-loop operation. For valves smaller than this minimum, the BRU was found to reach a limiting speed below design speed. This is due to the increased compressor exit pressure caused by the smaller valves. As this pressure increases, the compressor torque requirement also increases. This results in a lower accelerating torque and a lower final speed. These results are plotted in figure 2. The solid line represents the minimum valve size for a turbine inlet temperature of 945 K (1170⁰ R). Radiator outlet temperature was fixed at 266 K (480⁰ R) and the vent valve was assumed to discharge to a hard vacuum. At a turbine inlet temperature of 945 K (1700⁰ R), the BRU will reach rated speed only for vent valves sized to operate above the minimum-valve-size line. This curve is a function of turbine and compressor inlet temperatures. From these studies a theoretical vent valve was sized for 0.16-kg/sec (0.35-lb/sec) flow at an upstream pressure of 5.5 N/cm² (8.0 psia).

The succeeding analog studies were then made with this theoretical vent valve size. However, the valve contractor was allowed to choose a different size if it would result in

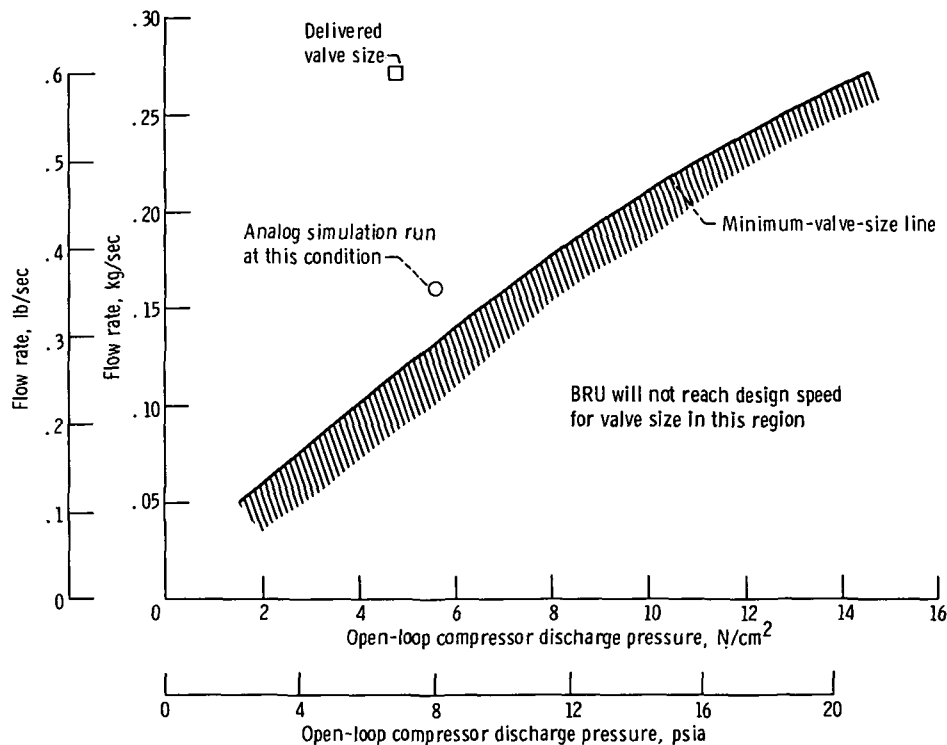


Figure 2. - Minimum vent valve size as determined by analog simulation. Turbine inlet temperature, 945 K (1700° R); compressor inlet temperature, 266 K (480° R).

a more reliable valve. The only requirement was that it be above the minimum-valve-size line. The delivered valve was sized for 0.27-kg/sec (0.6-lb/sec) flow at 5.2- N/cm^2 (7.5-psia) upstream pressure and 0.35- N/cm^2 (0.5-psia) downstream pressure. This is well above the minimum-valve-size line (refer to fig. 2); therefore, successful starts were expected to be attained easily. For this reason no further analog studies with the actual valve data were made.

Self-Sustaining Speed

Because of a limited gas supply during a space mission, it is desirable to start the system with the least possible amount of gas. If the injection valve were closed before rated speed was reached, less gas would be lost to space. There is, however, a minimum speed that must be attained before the injection valve can be closed. If injection were stopped before this speed was reached, the BRU would decelerate to zero speed. This minimum speed will be referred to as the self-sustaining speed. This speed is a function of turbine inlet temperature. The time and amount of gas needed to achieve successful starts is therefore dependent on self-sustaining speed.

Turbine work is dependent on inlet temperature. Variations in this temperature affect self-sustaining speed. Figure 3 shows that self-sustaining speed decreases for increasing turbine inlet temperature. The computer predictions were based on a vent valve size of 0.16 kg/sec (0.35 lb/sec) at 5.5 N/cm² (8.0 psia). The test results are for a vent valve size of 0.27 kg/sec (0.6 lb/sec) at 5.2 N/cm² (7.5 psia).

Figure 3 indicates that below 400 K (720° R), the BRU must reach at least 50 percent of design speed to be self-sustaining. This curve indicates the importance of a high turbine inlet temperature.

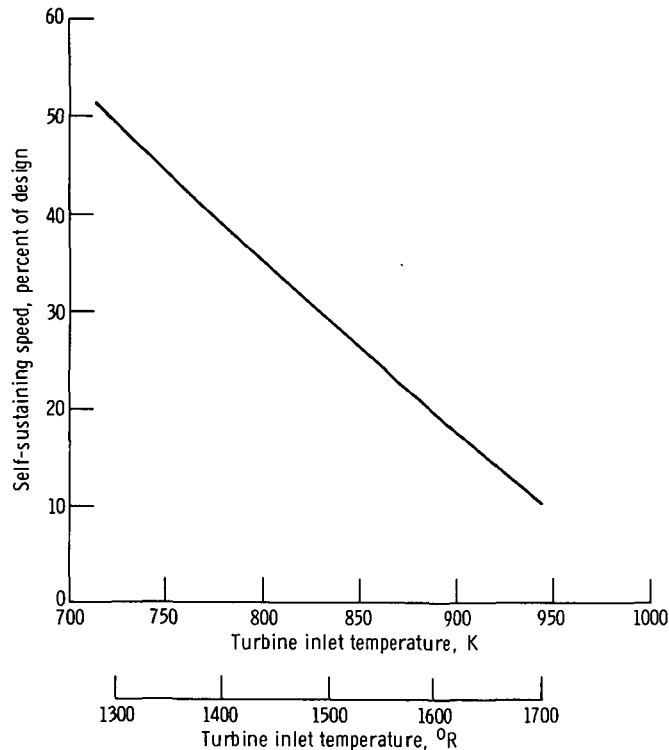


Figure 3. - Computer prediction of self-sustaining speed for range of turbine inlet temperatures. Compressor inlet temperature, 300 K (540° R).

START PROCEDURE

As mentioned previously, closing the injection valve above the self-sustaining speed but below rated speed will conserve gas. During starting, the butterfly valve is closed and the vent valve is open. The butterfly valve is a gas-actuated valve that is spring loaded to open. When it is closed, it will remain closed until the actuating gas is removed. When the vent valve is closed during starting, the pressure between the compressor discharge and the butterfly valve increases rapidly. The computer simulation has shown that at speeds below 50 percent of design, this procedure causes the compressor to approach a condition of oscillating flow known as surge. Because the effects of

surge on the gas bearings are unknown, this condition was avoided. This was accomplished by setting the cutoff speed greater than 50 percent of design. Thus, the minimum cutoff speed is not determined by self-sustaining speed, but is set by the surge condition.

Based on the results of these analog studies the following start sequence was selected and was successfully used in subsequent system testing:

- (1) Preheat the heat source to a temperature that results in a self-sustaining speed of 50 percent of design or less.
- (2) Close the actuated butterfly valve.
- (3) Open the vent valve.
- (4) Apply jacking gas to the bearings.
- (5) Open the injection valve.
- (6) At 50 percent of speed or greater, close the vent and injection valves, and remove the gas supply holding the butterfly valve closed.
- (7) After design speed is reached, bleed additional gas into the power system to bring the power level to design.

Start Results

Successful starts can be attained for various combinations of turbine inlet temperature and cutoff speed. However, there is a minimum temperature and minimum speed below which attempted starts will be unsuccessful.

Successful start region. - Computer predictions of the minimum temperatures and speeds for a successful start are shown in figure 4(a). These plots show two analog computer curves. The maximum open-loop speed curve shows the maximum speed the BRU will reach if the valves are left open. The self-sustaining speed curve shows the minimum speed that must be reached before the valves can be closed. The intersection of these two curves defines the minimum temperature required for a successful start, 650 K (1170° R). This condition alone is not sufficient for successful starts. The other necessary condition is that speed be above self-sustaining. These curves define a region of temperatures and speeds that will result in successful starts.

Figure 4(b) shows experimental data on the minimum temperature and speed for successful starts. Successful starts obtained occur in the region defined in figure 4(a). Also shown in figure 4(b) are three unsuccessful start attempts. In these unsuccessful starts a maximum open-loop speed greater than that predicted by the analog simulation was attained. This difference in speed is due to the difference in valve sizes. The valve used on the actual system was larger than the valve used on the simulation. The larger valve tends to keep compressor discharge pressure lower, allowing the BRU to reach a higher open-loop speed.

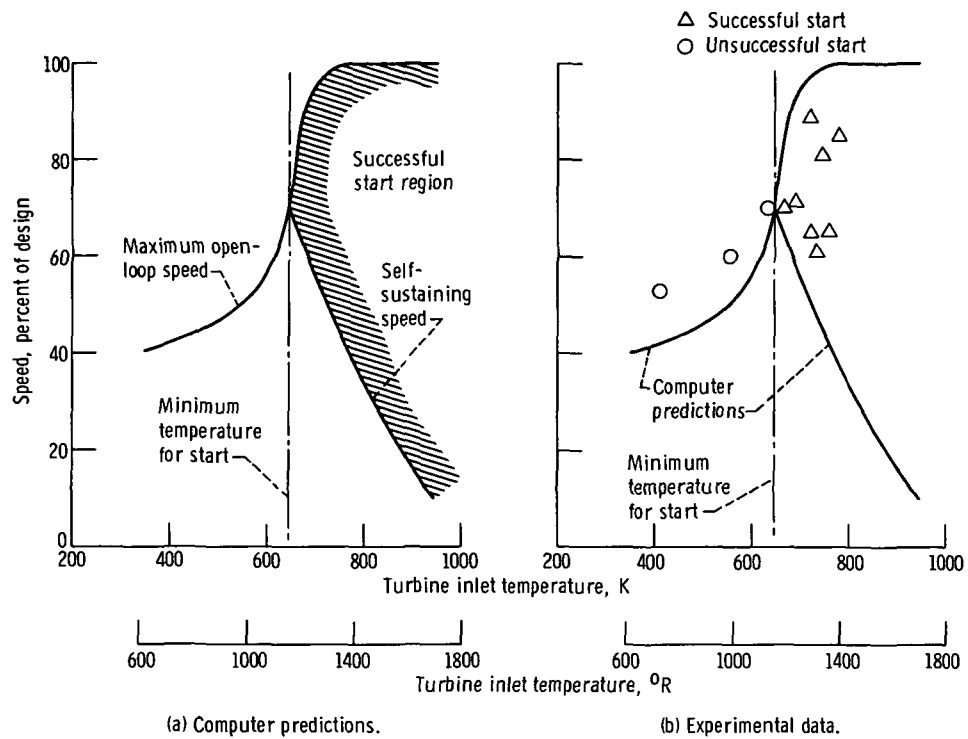


Figure 4. - Range of turbine inlet temperature and speed for successful starting of Brayton power system.

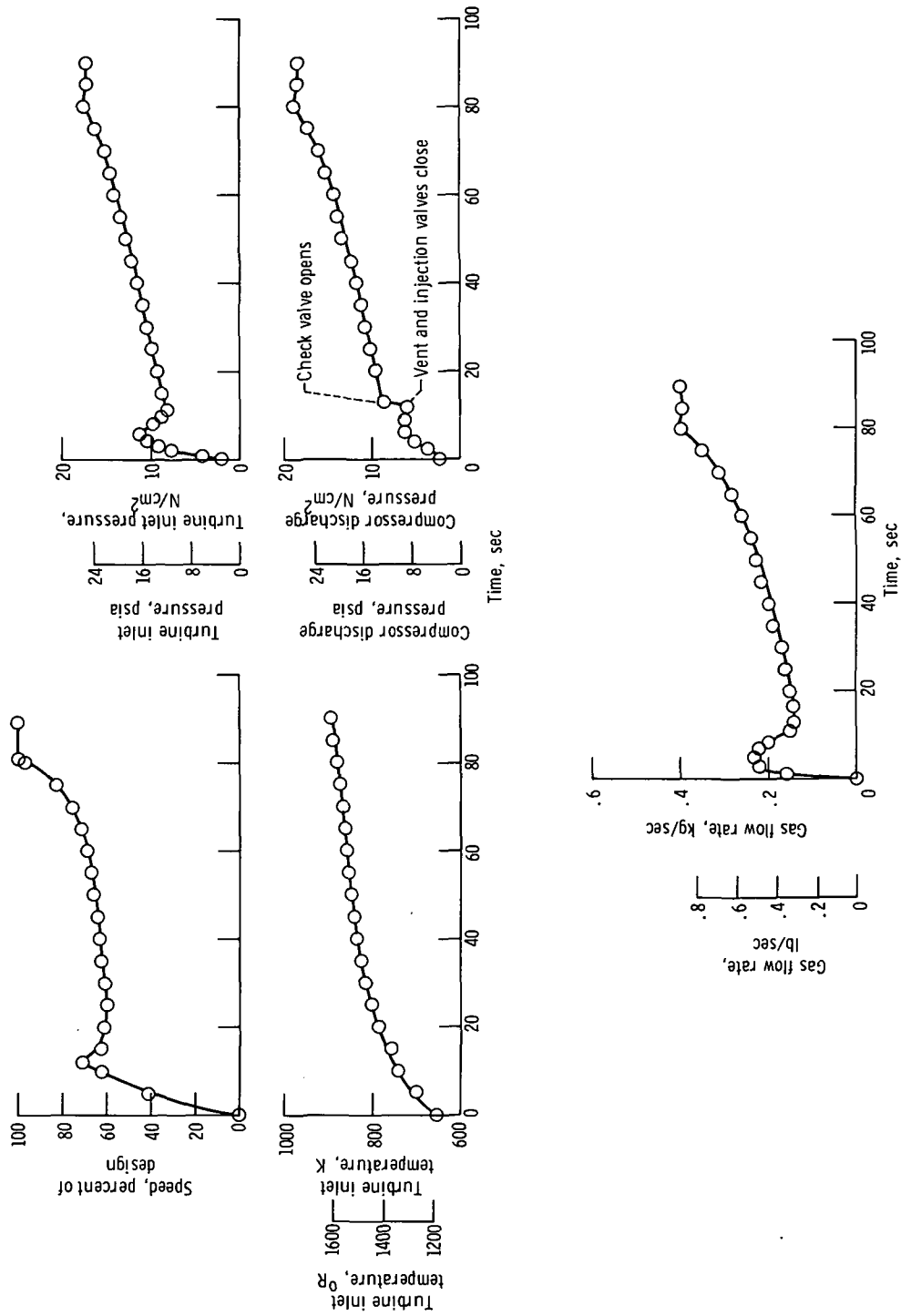


Figure 5. - Typical experimental startup. Compressor inlet temperature, 285 K (512° R).

Typical experimental start. - Data obtained from a typical experimental start are shown in figure 5. For this run the initial turbine inlet temperature was 660 K (1185° R) and compressor inlet temperature was 290 K (520° R). Injection cutoff was chosen to be 24 000 rpm (66 percent of design). The total starting time was 80 seconds. This start required approximately 3.6 kilograms (8 lb) of gas. After the BRU reached design speed, additional gas was injected to bring the system to its design operating pressure (31 N/cm² (45 psia) at the compressor discharge).

SHUTDOWN

Two shutdown modes exist for the Brayton system. The normal shutdown mode would be used for planned shutdowns. The emergency shutdown mode would be used to shut the system down in the event of a failure which might damage the system.

Guidelines for choosing a shutdown procedure were (1) to bring the BRU safely to zero speed from design speed as quickly as possible; (2) to use no additional hardware; and (3) to allow for restart.

Normal Shutdown

The Brayton power system can be shut down by overloading the alternator. This would bring the BRU to zero speed in about 30 seconds. However, because of the high temperatures throughout the system, the post-shutdown temperature transient could be harmful. The normal shutdown procedure avoids this problem by using the working gas to cool the components before bringing the BRU and therefore gas flow to zero. This is accomplished by removing heat input to the system while still operating the system. In effect, the power system is operating on the sensible heat contained in its heat-exchanger masses. This results in lowering the overall power system temperature.

Normal shutdown begins by removing power to the heat source. This allows system temperatures to decrease. During this procedure, electrical load is transferred to the parasitic load, which automatically adjusts for the loss in alternator output. When alternator power has decreased to about 1 kilowatt, full parasitic load (18 kW) is applied to the alternator. This causes BRU speed to decrease rapidly. At the same time, the vent valve is opened to exhaust all gas to space.

The normal shutdown procedure is summarized as follows:

- (1) Turn off the heat source and wait until alternator output power decreases to about 1 kilowatt.
- (2) Then apply hydrostatic gas to the bearings.

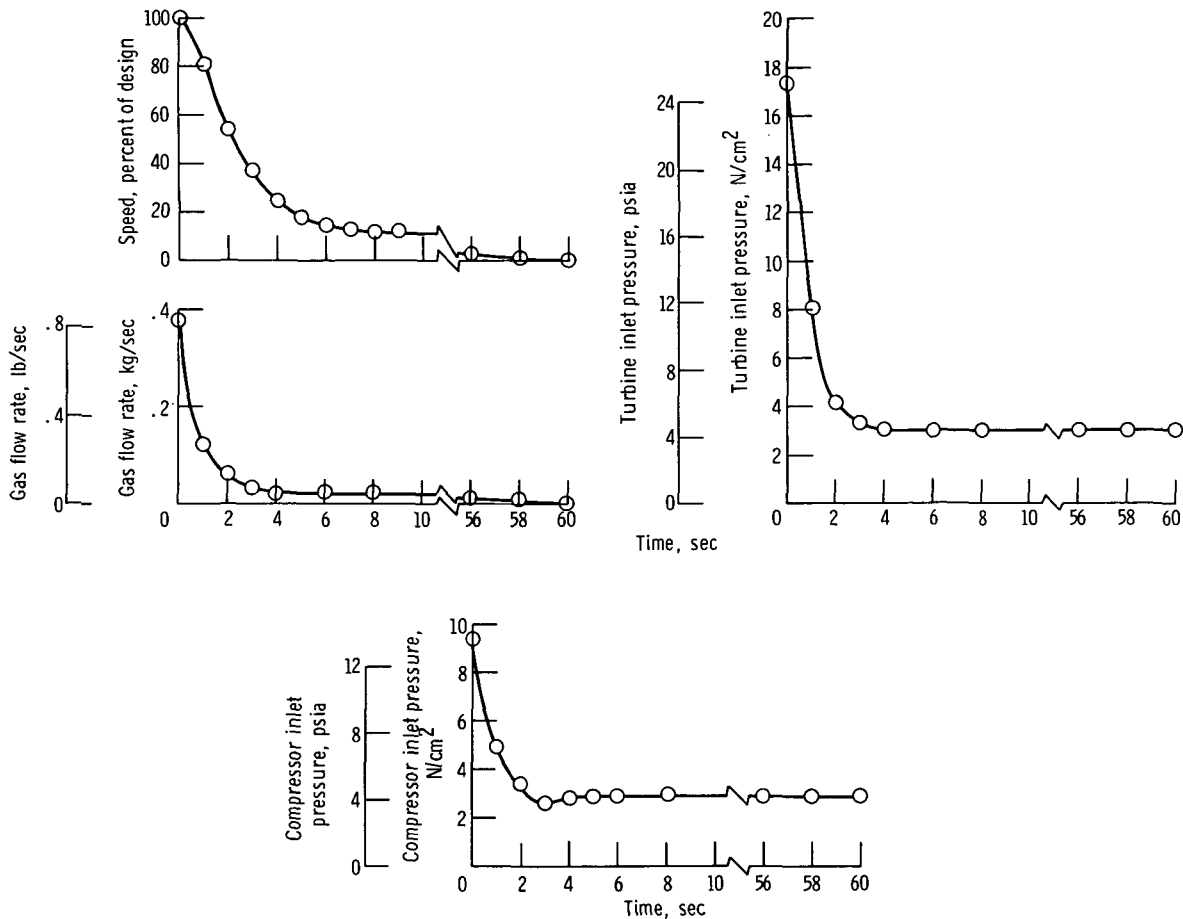


Figure 6. - Typical experimental shutdown.

(3) Apply full parasitic load (18 kW) to the alternator and open the vent valve.

(4) When zero speed is reached, turn off the gas to the bearings.

A typical experimental shutdown is shown in figure 6. At the time alternator output is at the 1-kilowatt level, full parasitic load is applied. Speed decreases to about 10 percent of design in 10 seconds. Because of the design of the voltage regulator, alternator power decreases as speed decreases. Therefore, the rate of change of speed decreases. At 10 percent of design speed, the only loads on the machine are caused by the compressor, bearing, and windage effects. This causes speed to decrease to zero in about an additional 50 seconds. The total shutdown time being of the order of 60 seconds.

Emergency Shutdown

The normal shutdown depends on overloading the alternator with parasitic load. If a failure, such as loss of alternator field supply, occurs in the system, the BRU will accel-

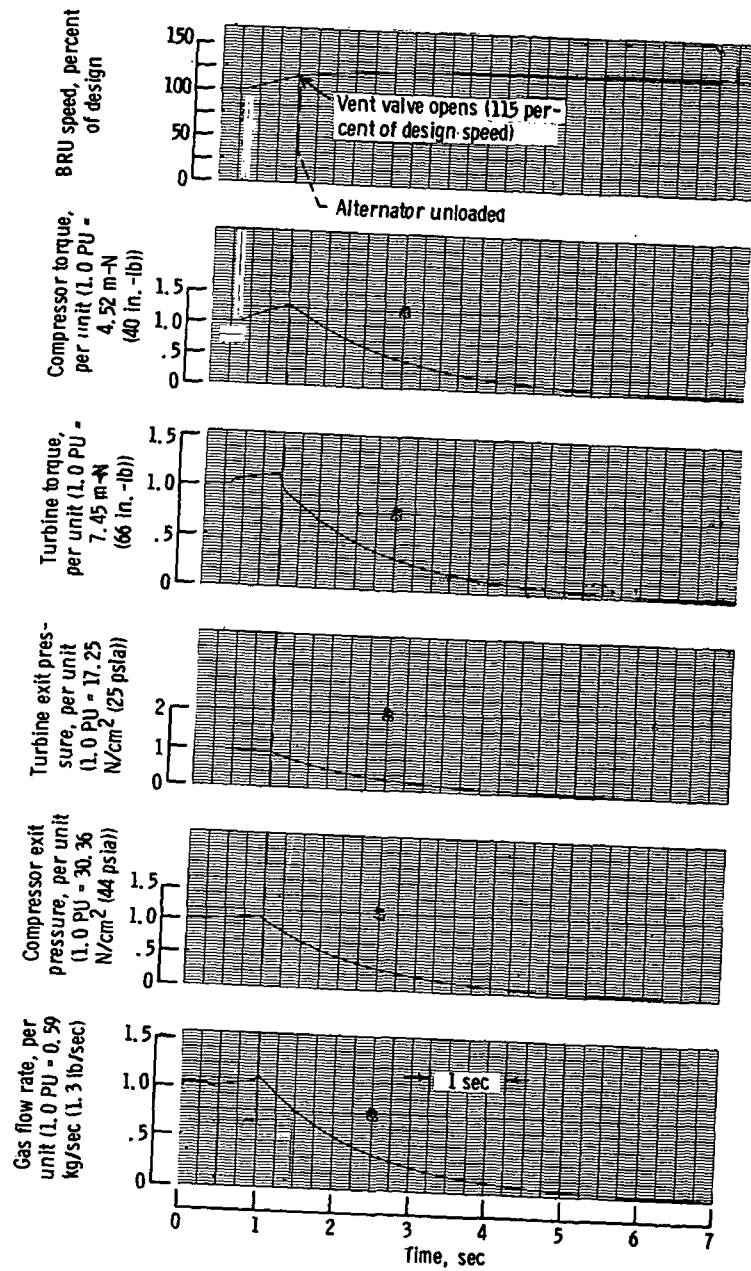


Figure 7. - Emergency shutdown as run on analog computer.

erate at an initial rate of 10 percent per second. At 115 percent of design speed, the engine controls automatically initiate an emergency shutdown. The procedure for this shutdown is to initiate the following actions simultaneously:

(1) Apply gas to the bearings.

(2) Open the vent valve.

(3) Turn off the heat source.

(4) Apply full parasitic load. (This will not be effective if overspeed is caused by alternator failure.)

This type of shutdown has never occurred. However, figure 7 shows the analog prediction of what would occur if the alternator became unloaded. With the alternator unloaded, BRU speed begins to increase. At 115 percent of design speed the emergency shutdown procedure is initiated. This shutdown was run on the analog computer with a constant turbine inlet temperature of 1140 K (2060° R) and the vent valve open to space (zero pressure). The entire inventory of gas is evacuated from the system within 5 seconds. This causes speed to level off at about 125 percent of design. If it is assumed that the only losses on the BRU are due to the bearings, calculations indicate that the BRU would take about 30 minutes to decrease to zero speed. While the BRU is rotating, hydrostatic gas must be supplied to the bearings at a rate of 0.0073 kg/sec (0.016 lb/sec) to support the shaft. This requires 13 kilograms (29 lb) of gas to be used during this shutdown. (Normal system operating inventory, by comparison, is 0.7 kg (1.5 lb).)

Alternate Emergency Shutdown Procedures

The preceding emergency shutdown procedure was devised on the basis of using no additional hardware other than that needed for startup and normal operation. Two alternate emergency shutdown procedures were studied to present the merits of each for trade-off analysis. The methods are compressor-inlet injection and compressor bypass.

Compressor-inlet injection. - The first procedure requires an additional valve between the gas-storage bottle of the gas management subsystem and the compressor inlet and involves injecting gas at the compressor inlet while venting gas at the compressor discharge. This has the effect of depriving the turbine of power while also loading the compressor.

The resulting transient in figure 8 shows that the BRU decelerates to zero speed in about 37 seconds. The compressor injection flow for this run was 0.16 kg/sec (0.35 lb/sec). The vent valve was sized for a flow rate of 0.16 kg/sec (0.35 lb/sec) at an upstream pressure of 5.5 N/cm² (8.0 psia) and zero downstream pressure. This shutdown requires about 6.0 kilograms (13 lb) of gas. However, the amount of time to reach zero speed depends on the size of the additional valve. During the shutdown, gas must be sup-

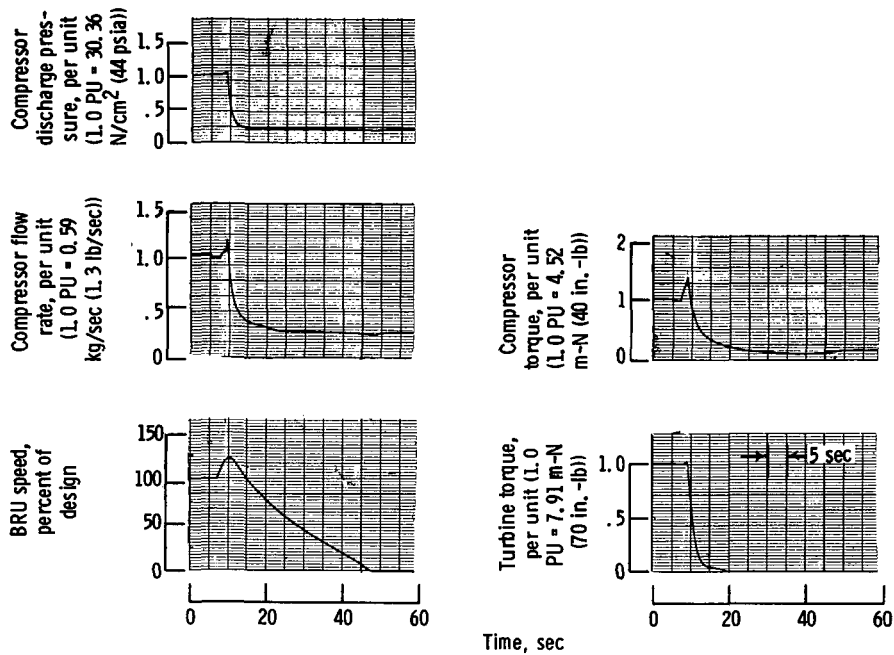
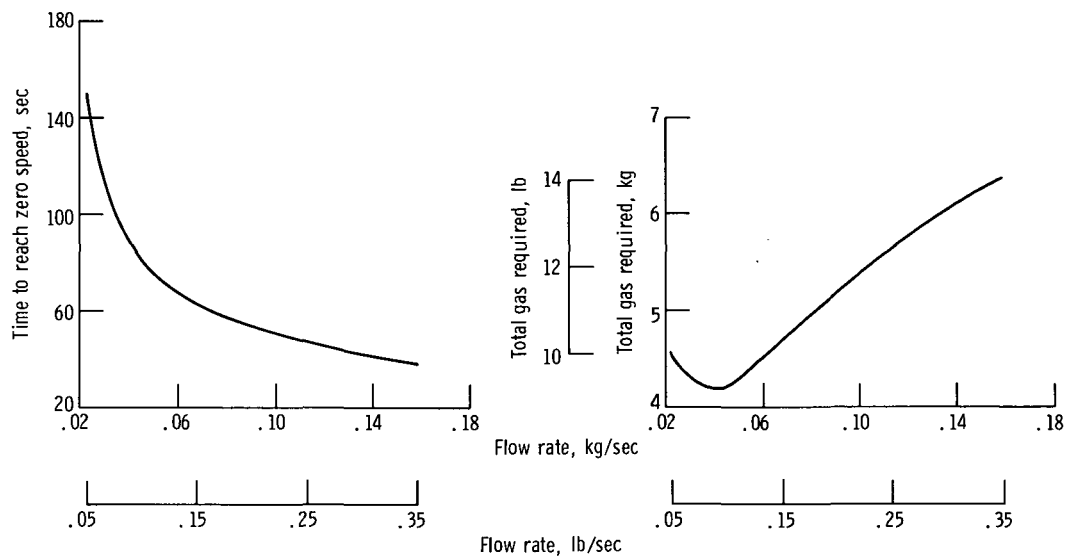


Figure 8. - Alternate emergency shutdown as run on analog computer. Additional injection flow, 0.17 kilogram per second (0.35 lb/sec).



(a) Time to reach zero speed for various flow rates.

(b) Total gas (injected plus bearings) required to reach zero speed for various flow rates.

Figure 9. - Characteristics of alternate emergency shutdown technique for vent valve with 0.16-kilogram-per-second flow rate at 5.5 N/cm² (8.0 psia).

plied at a rate of 0.0073 kg/sec (0.016 lb/sec) to support the bearings.

Figure 9(a) shows the relation between flow rate and the time to reach zero speed. Figure 9(b) shows the total amount of gas (including bearing gas) required to shut down at a specific flow rate. As shown in this figure, an optimum emergency shutdown (with respect to the amount of gas required) exists for a compressor injection flow rate of 0.45 kg/sec (0.1 lb/sec). It would require about 4.0 kilograms (8.8 lb) of gas and take about 80 seconds to reach zero speed. This amount of gas is about six times the design inventory of 0.68 kilogram (1.5 lb), but less than required by the selected emergency shutdown procedure.

Compressor bypass. - The second procedure can be used to shut down quickly and conserve gas. This method passes gas flow from the discharge of the compressor directly to its inlet. This results in overloading the turbine, which causes the BRU to decelerate to zero speed without venting gas. Studies indicate that a 2.5-centimeter (1-in.) diameter line would be sufficient to bring the BRU to zero speed in about 60 seconds. The only additional gas required would be the 0.45-kilogram (1.0-lb) supply to the bearings.

SUMMARY OF RESULTS

Two methods of starting the Brayton power system have been considered: (1) using the alternator as a motor to spin the Brayton rotating unit (BRU), and (2) spinning the BRU by forced gas injection.

The first method requires the use of an auxiliary electrical power source. An alternating voltage is applied to the terminals of the alternator to drive it as an induction motor.

The gas-injection starting method requires high-pressure gas storage and valves to route the gas flow to provide correct BRU rotation. Only gas-injection starts are discussed in this report.

An analog computer simulation was used to size hardware and to determine safe start and shutdown procedures. The simulation was also used to define the range of conditions for successful starts. Experimental data were also obtained under various test conditions. These data verify the validity of the start and shutdown procedures.

Start

As a result of the analog studies, the following Brayton power system gas-injection starting procedure was adopted:

- (1) Preheat the heat source to the desired temperature.
- (2) Close the butterfly valve.
- (3) Open the vent valve.
- (4) Apply hydrostatic gas to the bearings.
- (5) Open the injection valve.
- (6) At 50 percent of speed or greater, close the vent and injection valves and open the butterfly valve.
- (7) After design speed is reached, inject additional gas into the system to bring the power level to design.

Tests have verified that this procedure provides an effective means of starting the Brayton system. For a turbine inlet temperature of 660 K (1185° R) and an injection cut-off speed of 24 000 rpm, total startup time is 80 seconds.

Shutdown

Normal shutdown. - The normal shutdown procedure is as follows:

- (1) Turn off the heat source and wait until the alternator output power decreases to about 1 kilowatt.
- (2) Apply hydrostatic gas to the bearings.
- (3) Apply full parasitic load (18 kW) to the alternator and open the vent valve.
- (4) When zero speed is reached, turn off the gas to the bearings.

Tests have shown that this procedure provides an effective method of shutting down the Brayton power system. This procedure requires 60 seconds to bring the BRU to zero speed.

Emergency shutdown. - The emergency shutdown procedure is initiated in the event of a failure that causes the alternator to become unloaded. At 115 percent of design speed, the gas is vented from the system, limiting the maximum speed of the BRU to 125 percent of design speed. This shutdown requires about 13 kilograms (29 lb) of gas.

Two additional emergency shutdown procedures were studied on the analog simulation. The first requires an additional valve to be included at the compressor inlet to inject gas into the compressor. For this emergency shutdown method, injecting gas at a rate of 0.045 kg/sec (0.1 lb/sec) at the compressor inlet results in bringing the BRU to zero speed in 80 seconds. This shutdown procedure requires about 4 kilograms (9 lb) of gas.

The second alternate procedure is the compressor bypass method. A 2.5-centimeter (1-in.) diameter bypass line can bring the BRU to zero speed in about 60 seconds. This shutdown procedure requires about 0.45 kilogram (1 lb) of gas.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 13, 1972,
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